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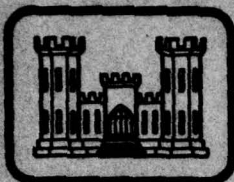
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MISCELLANEOUS PAPER EL-79-2

EFFECTS OF FREEZING TEMPERATURES AND FROZEN-GROUND CONDITIONS ON ENCLOSED-WIRE-IN-TUBE RESPONSE

by

Charles A. Miller

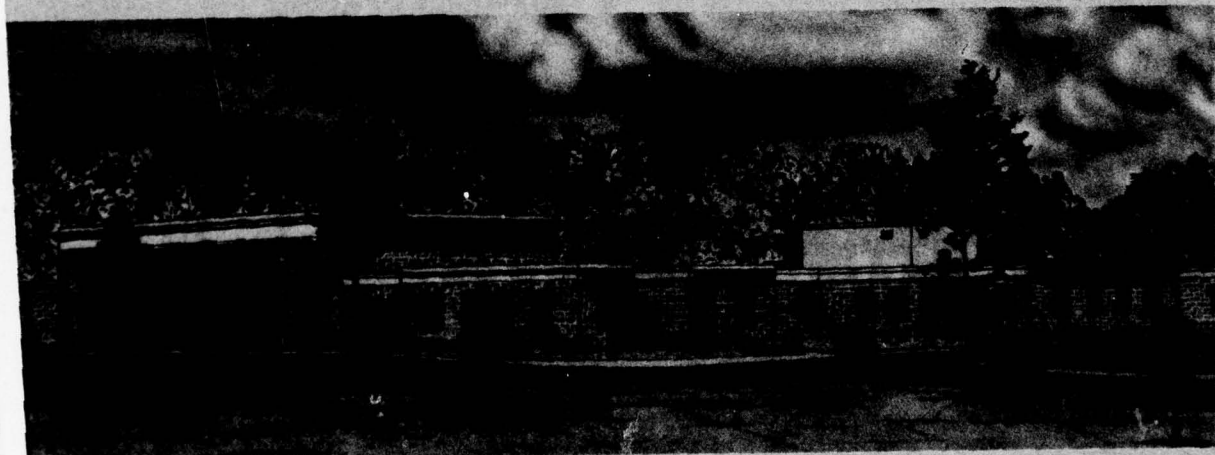
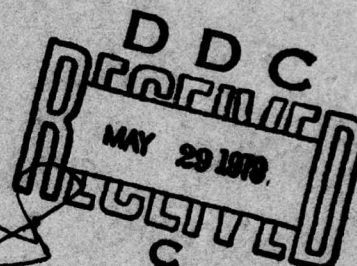
Environmental Laboratory

U. S. Army Engineer Waterways Experiment Station
P. O. Box 631, Vicksburg, Miss. 39180

April 1979

Final Report

Approved For Public Release; Distribution Unlimited



Prepared for Rome Air Development Center
Griffiss Air Force Base, N. Y. 13440

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Miscellaneous Paper EL-79-2	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) EFFECTS OF FREEZING TEMPERATURES AND FROZEN- GROUND CONDITIONS ON ENCLOSED-WIRE-IN-TUBE RESPONSE,	5. TYPE OF REPORT & PERIOD COVERED Final report, Nov 77-Sep 78	
6. AUTHOR(s) Charles A. Miller	7. PERFORMING ORG. REPORT NUMBER	
8. PERFORMING ORGANIZATION NAME AND ADDRESS U. S. Army Engineer Waterways Experiment Station Environmental Laboratory P. O. Box 631, Vicksburg, Miss. 39180	9. CONTRACT OR GRANT NUMBER(s)	
10. CONTROLLING OFFICE NAME AND ADDRESS Rome Air Development Center Griffiss Air Force Base, N. Y. 13440	11. REPORT DATE April 1979	
12. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 45 p.	13. NUMBER OF PAGES 40	
14. DISTRIBUTION STATEMENT (of this Report) Approved for public release; distribution unlimited.		15. SECURITY CLASS. (of this report) Unclassified
16. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report) WES-MP-EL-79-2		
17. SUPPLEMENTARY NOTES MIPR-FQ7649-80-010		
18. KEY WORDS (Continue on reverse side if necessary and identify by block number) Enclosed-wire-in-tube Frozen soils Sensors Temperature effects Transducers		
19. ABSTRACT (Continue on reverse side if necessary and identify by block number) A study was conducted to determine the effects of below-freezing temperatures and frozen ground on the output response of the enclosed-wire-in-tube (EWIT) sensor. The analysis of the results of below-freezing response tests indicated that low temperatures (neglecting the medium) did not cause a noticeable change in EWIT response. The analysis of the results of frozen soil tests showed that an increased depth of frost penetration caused a corresponding decrease in EWIT response by as much as 30 db. The analysis of the results (Continued)		

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20. ABSTRACT (Continued).

of response tests conducted in soft and rigid unfrozen ground where shear moduli approximated that of unfrozen and frozen ground, respectively, showed that an increase in the rigidity of the emplacement media caused a decrease in EWIT response that was comparable to the decrease experienced under frozen-ground conditions.

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PREFACE

This study was conducted by the U. S. Army Engineer Waterways Experiment Station (WES) for the Rome Air Development Center, Griffiss Air Force Base, New York, under MIPR No. FQ761980010. A portion of this study was conducted for WES at the U. S. Army Cold Regions Research and Engineering Laboratory (CRREL) under Intra-Army Order No. WES-78-8.

The work was conducted during the period November 1977 to September 1978. Until February 1978, this work was under the general supervision of Messrs. W. G. Shockley, former Chief, Mobility and Environmental Systems Laboratory; B. O. Benn, Chief, Environmental Systems Division (ESD); and Dr. L. E. Link, Chief, Environmental Research Branch (ERB). The ERB and ESD are now part of the recently organized Environmental Laboratory of which Dr. John Harrison is Chief. Project manager was Dr. D. H. Cress, ERB. Project leader was Mr. C. A. Miller, ERB. This report was written by Mr. Miller.

At CRREL the principal investigator was Mr. John Stubstad, Engineering Systems Division (ESD). Chief technician during tests conducted at CRREL was Mr. G. Durrell, ESD.

Commander and Director of WES during the course of this study and the preparation of this report was COL J. L. Cannon. Technical Director was Mr. F. R. Brown.

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EFFECTS OF FREEZING TEMPERATURES AND FROZEN-GROUND CONDITIONS
ON ENCLOSED-WIRE-IN-TUBE RESPONSE

PART I: INTRODUCTION

Background

1. During the last several years, buried-line sensor systems have played an increasingly significant role in support of perimeter security. One of several candidates for use in the next generation of buried-line sensors is the enclosed-wire-in-tube (EWIT) sensor. Investigation of the potential role of the EWIT in perimeter security has been directed by the Rome Air Development Center (RADC), New York. This study addressed part of their investigative effort.

2. The EWIT transducer consists of a small teflon-coated wire that is loosely laid inside a 0.65-cm-diam copper tube. It is typically 100 m in length and buried at a depth of 23 cm. The transducer acts as a distributed line capacitor in which the relative movements of the wire and the points of contact with respect to the side of the tube cause proportional changes in capacitance. These capacitance changes are converted into voltage changes by means of the electret action of the teflon insulation.

3. The response of the EWIT transducer has been characterized as having a number of modes by which transducer response is produced. These modes and response ranges are as follows: displacement mode (0-1 Hz), intrusion mode (1-20 Hz), strumming mode (20-100 Hz), and accelerometer mode (greater than 100 Hz).^{*,**} Regardless of the mechanism, the EWIT

* R. Falk and W. F. Gavin, Jr., "Evaluation of An Enclosed Wire Buried Line Transducer," In-House Report, RADC-RT-76-131, Jul 1976, Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, New York.

** R. D. Erianne, "Enclosed Wire-In-Tube (EWIT) Logic Design I," Final Technical Report, RADC-TR-77-426, Volume I (of two), Dec 1977, Rome Air Development Center, Air Force Systems Command, Griffiss Air Force Base, New York.

is capable of responding to excitations ranging from less than 1 to greater than 20,000 Hz. The longitudinal sensitivity has been shown to vary by as much as 25 db.* This variation in sensitivity along the length of the cable has been attributed to the inconsistency of the electret potential on the teflon insulation as received by the manufacturer. It is also suspected that the random variation in the points of contact of the inner wire can cause variations in response along the sensor.

4. During the period of December 1976 to April 1977, a series of EWIT field tests were conducted at an RADC test site located at Griffiss Air Force Base, New York.** The analysis of the results of these tests indicated that numerous dead spots (decreased response of 20 to 30 db) occurred at various sections along the transducers in which very low signal response at low frequencies (less than 5 Hz) was obtained during frozen-ground conditions. This negligible low frequency response was observed in areas where frost penetration was the deepest. It was hypothesized that these dead spots could be attributed either to poor sensor-ground coupling or to wire-to-tube freeze-up caused by water seepage into the transducer.

5. Because of the anomalous response of the EWIT in the frozen-ground conditions, RADC requested the U. S. Army Engineer Waterways Experiment Station (WES) to investigate the dependence of EWIT response on temperature irrespective of the emplacement media (i.e., excite the EWIT in a manner for which the only significant variable change during tests was temperature) and examine the effects of high-shear-strength media (having a shear modulus on the order of that for frozen grounds) on EWIT response.

Purpose and Scope

6. The study reported herein was designed to determine the effects of the following conditions on the response of the EWIT sensors:

* Falk and Gavin, Jr., op. cit., p. 3.

** Erianne, op. cit., p. 3.

- a. Below-freezing temperatures irrespective of emplacement media.
- b. Emplacement in frozen soil.
- c. Emplacement in high-shear-modulus media (approximating the shear modulus of some frozen soils).

7. The various EWIT response experiments were conducted at the WES and the Cold Regions Research and Engineering Laboratory (CRREL). In these tests, two types of EWIT sensors were used: the standard cable and a special cable in which special efforts were taken to purge the sensors of moisture. All test cables were 15 m in length (the standard length is 100 m). At CRREL the effects of below-freezing temperatures and frozen soil were studied. At WES, tests were conducted to study the effects of high-shear-modulus soil on EWIT performance.

8. For the freezing-temperature tests (at CRREL), a special vibration mechanism was constructed to transmit repeatable sine wave motions in sections of the sensors. For the frozen-soil and high-shear-modulus tests, transient seismic signals were produced by personnel walking along the cable and with a pendulum mechanism designed to transmit repeatable low-frequency seismic signals comparable to that of a man creeping.*

9. This report describes the equipment used, site conditions, and tests performed, and gives the experimental results and the analysis of the data.

* C. A. Miller, "Preinstallation Survey Guide for MAID-MILES System," Miscellaneous Paper No. M-78-6, Jun 1978, U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

PART II: BELOW-FREEZING RESPONSE TESTS

Test Equipment and Facilities

10. Test equipment was designed and constructed to study the dependence of EWIT response (standard and special design) on temperature in the range from -10 to 15°C. The concepts for the design of the test equipment were the following:

- a. Temperature variations should have a negligible influence on the mechanism used for excitation of the sensor.
- b. The amplitude of vibration of the sensor should be representative of the range of seismic motions that usually occur in natural soils from transient forces produced by a man walking.

Vibration mechanism

11. The concept for exciting the EWIT's consisted of attaching an EWIT sensor to a beam and vibrating the beam. Figure 1 is a schema of a beam-spring-mass system for vibration of the EWIT's. This mechanism consists of a simply supported aluminum beam (15 by 10 cm, wide flange) with a spring-mass system connected to the midspan of the beam. According to the spring constant (newtons/cubic metre) of the springs and the weight of the mass, when the mass is moved vertically from its point of equilibrium, it will oscillate vertically in a sinusoidal motion at a specific frequency. The initial vertical distance that the mass is moved from its equilibrium position determines the peak-to-peak sine wave forces that are initially applied to the beam.

12. As the beam reacts to the sine wave forces, it deflects vertically in a manner complementary to the mass. The maximum peak-to-peak deflection of the beam is at its midspan with zero deflections occurring at the supports. During the design of the system, it was assumed that the deflection of the beam could be derived from standard strength of materials equations for a static point load applied at the midspan of a simply supported beam.

13. The beam-spring-mass system was designed to generate vibrations at frequencies of 1, 3, 5, 7, and 10 Hz. The system design consisted of:

- a. Specifying the maximum deflection of midspan of the beam at each of required frequencies based on the desired particle velocities.
- b. Specifying desired beam parameters (i.e., length, type of material, moment of inertia, and Young's modulus) based upon the midspan deflections specified in a. above.
- c. Specifying spring constants and size of masses to be used for the selected frequencies to obtain the desired beam deflections using standard strength of materials and vibration equations.

14. The criteria for the beam vibrations were based on the range of 0.01 to 0.1 cm/sec particle velocity, which is a nominal range of maximum amplitudes induced from the footfall of a man walking on moderately rigid soils several metres from a transducer. The spring and mass specifications were computed to develop the necessary forces for the beam specified to obtain the particle velocities specified. The selection of the spring-mass combinations was made so that the initial vertical movement of the masses would be repeatable during the tests. A compromise set of particle velocities and beam deflections that proved reasonable for these purposes is presented in Table 1. The beam specifications and computed spring-mass specifications for the beam-spring-mass system are also presented in Table 1.

15. To secure the EWIT sensor to the beam, a laminated wood and foam plank was constructed. The EWIT was laid along the center of the longitudinal axis of the beam (Figure 1); the plank was laid over the EWIT with the foam side against the sensor. The plank was secured with metal straps and bolts so that a constant pressure would be applied along the 2-m section of EWIT being tested. A geophone was fastened to the beam with a pedestal that bridged the laminated plank and EWIT at the midspan of the beam.

16. The spring-mass system constructed in this way (using a single spring) caused excessive sidesway of the mass, particularly for frequencies greater than 1 Hz (3, 5, 7, and 10 Hz). For this reason, two springs (Figure 2) were subsequently used for each of these systems in which each spring had one-half of the design spring constant given in Table 1. During the conduct of the tests, springs were aligned

vertically below the beam using a clamping fixture on the beam and on the floor. The clamping arrangement on the floor was constructed in a fashion so that the lower spring would be in tension at the lowermost position of the mass during vibration.

17. Prior to the conduct of the freezing-temperature tests, pre-experiment tests were performed to evaluate the performance of the beam-spring-mass system with respect to the design specifications. To accomplish this, the output from the geophone (see Figure 1) and the peak-to-peak displacement of each spring-mass combination were recorded. From these data the frequency and amplitude (centimetres per second) of the motion of the beam at its midspan were determined. These measured data are presented in Table 2, which shows that the measured velocities at the midspan compared favorably with those specified for each frequency tested.

Cold room facility

18. The beam-spring-mass system described in the previous section was placed in a cold room chamber capable of keeping specified temperatures and humidities to within ± 10 percent. During the tests, the temperature of the room was monitored and recorded. During the warm-temperature tests, the room was kept at 15°C ; during the below-freezing tests, the room temperature was -10°C .

Instrumentation equipment

19. Amplifying, filtering, and recording equipment used during these tests consisted of the EWIT sensor, a geophone, low-pass filters, high gain voltage amplifiers, a magnetic tape recorder, and a hard copy pen plotter.

20. For the EWIT sensor, a preamplifier, a postamplifier, and a filter system designed especially for the EWIT were used. The pre-amplifier was a charge amplifier designed to provide a constant gain of 100 (40 db). The filter network consists of selectable high-pass filters (either 0.015 or 1.25 Hz) and selectable low-pass filters (2.5, 5, 10, or 20 Hz). The EWIT signal output was amplified through selectable gains of 40, 50, 60, 70, and 80 db.

21. The geophone used in these tests was a Mark Products L4-1D

with a resonant frequency of 0.5 Hz. A Rockland Analog Filter (Model 1200) and a NEFF/DC amplifier were used for recording of the geophone signal.

22. The recording equipment consisted of a Hewlett-Packard Model 3963A tape recorder and a Gould Model 481 brush recorder. Output data from both the geophone and the EWIT sensor were recorded by both recorders. A voice narrative of the test in progress was recorded on the tape recorder.

23. As stated in paragraph 6, standard and special EWIT sensors were tested. These sensors were 15 m long. An impedance-matching capacitor was attached to both types of EWIT sensors so that the output impedance of the 15-m sections would be equivalent to the standard length 100-m sensors.

Conduct of Test

24. Response tests were performed on the standard and special sensors. Response measurements for each kind of sensor were obtained by vibrating five 2-m sections evenly spaced along each EWIT. For each section of each sensor, response tests were performed at 1-, 3-, 5-, 7-, and 10-Hz beam oscillations. The tests were performed first in the warm temperature (15°C) environment and then in the cold temperature (-10°C) environment.

25. This warm-cold sequence was followed by a sequence in which sensors were subjected to alternate 24-hr periods of warm and cold temperature environments during which response measurements were not obtained. This was followed by a third sequence of warm and cold temperature environments for which two alternate warm and cold tests series were performed. That is, the latter sequence consisted of conducting the vibration tests in the warm environment, followed by the cold environment, followed again by the warm and cold environments.

26. During and immediately after the conduct of the cold room tests, problems occurred with the electrical connections on the EWIT sensors. After a small number of connects and disconnects of the EWIT

sensor (on the order of two or three such actions), the insulation material surrounding the center pin of the sensor cracked. In one case the insulation deteriorated to the extent that the pin was pushed into the interior of the standard sensor. The sensor was replaced by the alternate standard sensor during the remainder of the cold room tests.

27. After the cold room tests were completed, it was noted that the other sensors used during these tests had also exhibited some cracking in the insulation surrounding the center pin. Such cracking could allow migration of water vapor into the sensor.

Results and Analysis of Tests

28. Comparisons were made of geophone output (centimetres per second $\times 10^{-3}$) and EWIT response (microvolts) using sample points taken from each test. The data were compiled according to sensor type, temperature conditions, and beam vibration frequency. The results of these tests showed that for a given clamping arrangement the 2-m sections of EWIT responded in proportion to the amplitude of vibration. This is demonstrated for the specially constructed EWIT in Figure 3, where the enclosed linear-shaped areas containing two to four sample points represent measured responses of the special EWIT for different amplitudes of the beam vibration (geophone output) for a single clamping arrangement. The tests were for the cold-temperature environment for 3-Hz vibrations. The data show that a large variation in response occurred during changes of the clamping of the cable from section to section. This variation may be caused by the relocation of the points of contact of the teflon-coated wire (paragraph 3) during the reclamping operation.

29. To describe the sensitivity of the EWIT to the beam vibrations, it seemed desirable to reduce the results for the large number of samples to a single best-fit line indicating the proportional increase in response of the EWIT's for the various environments and frequencies represented in the testing. The selected approach for obtaining a best-fit line was to determine the least squares fit line through the origin. The least squares fit line for the samples presented in Figure 3 is also presented

in the figure. As shown in the figure, the slope of the least squares fit line is a reasonable average of the slopes for the sample points for a single clamping arrangement. Data points and least square fit lines are presented for the special and standard EWIT's for the indicated environmental conditions for each test frequency in Figures 4 through 7. The slope of the least square fit lines can be interpreted as the sensitivity of EWIT response for that test condition. In the subsequent discussion, the term sensitivity will be used to refer to such slopes. The degree of scatter in Figures 4 through 7 combined with the fact that the least squares fit lines compare reasonably well between the special and standard EWIT's shows that the variation in response for each EWIT in either warm or cold environments greatly exceeded any apparent difference in response attributable to the warm or cold environments.

30. Observation of the least squares fit lines for the 1-, 3-, 5-, 7-, and 10-Hz frequencies suggests that as the frequency increases, the sensitivities decrease. Therefore, the sensitivity of the sensor system to the beam motion is frequency dependent. Although the data are not specifically identified for all comparisons in this report, this trend was particularly apparent for tests made on individual sections of the sensor (Figure 3) where the physical position (orientation) of the cable was not changed while the frequency was changed (see paragraph 29).

31. Figure 8 presents a plot of the sensitivities as a function of beam frequency. Figure 8 shows that the sensitivities of the EWITs were affected little by the freezing temperatures of the cold room facility because they were tightly grouped at each frequency relative to the total range in variation in the slopes evident in the example presented in Figure 3. The sensitivities for the cold room tests were neither consistently greater nor less than those for the warm room tests. The dotted line presented in this figure represents the computed sensitivities of sensor response to sensor motion if the sensor responds in direct proportion to displacement. The dotted line is normalized to the average sensitivity for the 1-Hz frequency. The close agreement between the measured sensitivity and the computed sensitivity (assuming response proportional to displacement) indicates that, within the range

of frequencies tested (1 to 10 Hz), the voltage output of the EWIT sensors responded in proportion to the amplitude of the displacement of the transducer during vibration. This indicates that the dominant mode for sensor response was the displacement mode referred to in paragraph 3.

32. To further investigate the sensitivities of the EWIT's along their length, the average sensitivities were obtained for each of the five vibrated sections (paragraph 24) along the EWIT. Figure 9 presents the mean EWIT sensitivities as a function of the five 2-m sections for the sensors tested. In this display, the sensitivities were computed for the five sections of each sensor and for the signals obtained from the 5-Hz beam vibrations. This display suggests that the longitudinal sensitivity of the standard EWIT sensor was more uniform than the sensitivity of the specially constructed sensor. This display also shows that the freezing temperatures did not reduce the response of the sensors since the average EWIT cold sensitivities are not consistently greater or less than those of the warm sensitivities across the frequency range considered.

Summary of Analysis of Cold Room Tests

33. The results of the below-freezing response tests indicate that:

- a. Below-freezing temperatures did not cause a large decrease in sensor response for either type of EWIT sensors tested.
- b. The relative sensitivity of the sensors (i.e., voltage output versus particle velocity) decreased in direct proportion to the increase in vibration frequency. This variation in EWIT response with frequency indicates that in the tests conducted the mechanism of sensor response was the displacement mode. Within this mode, the response of the EWIT sensor appears to be proportional to particle displacement instead of particle velocity.
- c. The electrical connections on the EWIT sensors are easily broken. The cracking of the insulation that surrounds the inner pin could cause the encroachment of water vapor to the interior of the sensor.

PART III: FROZEN-SOIL TESTS

34. The main objective of tests discussed in this portion of the study was to determine the change in EWIT response due to frost penetration through a soil. The main difference between these tests and those conducted during previous studies* was that the environmental characteristics (i.e., soil type, soil strength, moisture content, and depth of frost) could be more closely controlled and monitored throughout this test sequence than during the outdoor tests discussed in Erianne.*

Test Material and Equipment

35. A silty sand was selected for the test medium because its strength properties could be quite well defined when frozen. Furthermore, it was convenient to obtain and install at the CRREL installation. The grain-size distribution curve for this soil is given in Figure 10.

36. Various soil tests were conducted on sample specimens of this material to determine an acceptable moisture content for which moisture migration and frost heave would not be a problem. A soil moisture content of approximately 8 percent was selected as having sufficient moisture to provide a high shear strength without excessive frost heave. At this moisture content the unfrozen and frozen compressive strengths of the silty sand were approximately 2400 kilopascals (25 tons/ft²) and 7200 kilopascals (75 tons/ft²), respectively.

37. The soil was placed within a wooden container with inside dimensions of 4 × 5 × 1.2 m. During emplacement of the soil, two sets of thermocouple devices were placed at 2.5-cm depth intervals for monitoring the depth of frost penetration. After the container was filled with uniformly compacted soil, trenches were dug for the installation of the EWIT sensors.

38. Four sensors were installed within the soil bed; two were buried at a depth of 46 cm and two were buried at a depth of 23 cm. As

* Erianne, op. cit., p. 3.

shown in Figure 11, the 23-cm-deep sensors were located directly above the 46-cm-deep sensors. The sensors labeled E1 and E2 were the specially manufactured sensors while E3 and E4 were the standard sensors. Sensor E3 was the sensor that suffered the complete connection failure described in paragraph 26. Before the connection was repaired, a special effort was made to introduce very moist air (70 percent relative humidity at 30°C) into the tube. Special connectors were placed on the sensors to alleviate the problems that occurred in the cold room tests.

39. After installing the sensors and backfilling the trenches to the surface, a plastic cover was placed over the soil to reduce evaporation of moisture. Specially constructed refrigeration panels were placed over the container for the freezing process. Refrigeration panels were placed directly on the plastic cover and then covered with 15 cm of fiberglass insulation. Ten centimetres of styrofoam insulation was placed on the vertical sides of the container. The test bed was secured in this configuration during freezing. The rate and depth of frost penetration were controlled by refrigeration controls located adjacent to the test bed.

40. All data collected from these tests were recorded using the EWIT preamplifier, EWIT postamplifier, and Hewlett-Packard Model 3963A recorder described in paragraph 22.

Conduct of Tests

41. The soil was frozen from the surface at a rate of approximately 5 cm per day. The EWIT response measurements were obtained at frost penetration depths of 15, 28, 41, and 56 cm during the freezing process. The soil bed was then allowed to freeze to a depth of 103 cm, after which the thawing process was begun. Thawing occurred from the top at a rate of approximately 12 cm per day. As the soil thawed, sensor response measurements were made at thawed soil depths of 11, 16, 27, 34, and 76 cm and when the soil was completely thawed.

42. Tests were conducted using two different types of stresses: those of a man walking and those of a pendulum device constructed to

produce low-frequency (0.5-Hz) calibrated stress signals similar to those of a man creeping. The pendulum device is referred to as the calibrated creeper. Tests were performed using these signal sources along a line located directly above the sensors. Figure 12 is a schema of the locations where tests were conducted.

43. The tests conducted at the specified depths of frost penetration (or thaw) were conducted to determine the change in EWIT response in frozen ground as a function of the following:

- a. Changes in frost and thaw depth from the ground surface.
- b. Changes in burial depth of the sensor.
- c. Different sensors at the same burial depth.
- d. Location of the stress source along a single sensor (longitudinal variation).

Results and Analysis of Data

44. Comparisons were made of the outputs of the four EWIT sensors (microvolts) and the frost depth and thaw depth for the man-walking tests conducted directly over the sensors. Comparisons were also made of EWIT output versus frost depth for the calibrated creeper tests conducted at points A, B, and C shown in Figure 12. During the data reduction and tabulation, the output signals were low-pass filtered to obtain maximum resolution within the frequency bandwidth found to be most affected by frozen ground.* The results of these comparisons are shown in Figures 13 through 16. The EWIT responses for man walking for each frost or thawing depth were obtained by averaging four or five maxima measured off of the signature of a man walking the 5-m length of the EWIT (directly over the sensors).

EWIT response versus frost and thaw depth

45. The responses of the EWIT to the very low frequency of the calibrated creeper (0.5 Hz) were erratic. In a few tests, the EWIT response to the calibrated creeper behaved in the expected manner, such

* Erianne, op. cit., p. 3.

as for location B, Figures 13 and 14, and for location A, Figure 15. However, its responses tended to be very much less than for those of the man walking. Such responses to very low frequencies in rigid ground certainly detract from application of the EWIT for intruder detection in rigid media. Because of the inconsistency in EWIT response to the calibrated creeper, the subsequent analysis used the results obtained from the man-walking tests. For the man walking, the response of the EWIT sensors decreased with increase of frost depth. The change in output was 31, 23, 22, and 20 db for sensors E1, E2, E3, and E4, respectively. The drop in EWIT response is comparable to the dead sections described in previous studies (paragraph 4).

46. As shown in Figure 13, the greatest change in output from completely thawed to the frozen condition occurred for the most sensitive sensor (E1). Also, the minimum response levels for all four sensors approached a constant and were relatively the same. These minimum signal levels occurred after the thawing process was begun but before the thawed depth reached the sensor burial depth. This decrease in signal level after the termination of the freezing cycle was attributed to the fact that observed soil temperatures continued to decrease with depth for a period of time after the freezing process was ended.

47. As the depth of thawed material approached the depth of burial of the sensors, output levels increased again toward voltage levels obtained from the completely thawed tests. Both E1 and E3 (23-cm burial depths) experienced their highest signal output before the material was completely unfrozen. It is assumed that this higher signal level was the result of variations in the source input. This variation in maximum signal output is within the range in variation of man-walking signals described in previous studies.*

Variation in response as
related to depth of burial

48. As shown in Figures 13 through 16, the outputs of the deeper

* D. H. Cress, "A Study of MILES Response" (to be published), U. S. Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

sensors (E2 and E4) were appreciably lower than the sensors buried at 23 cm (E1 and E3). These data also show that, as frost depth increased, the decrease in response of the deeper sensors was not as severe and that the response of all four sensors approached approximately the same level. However, these lower response levels were of the same magnitude as the background noise level of the system.

Difference in signal output
with different sensors

49. A comparison of the maximum signal levels of sensor pairs located at the same burial depth for the man-walking tests shows that the response characteristics of the sensors were relatively the same. The variation in signal response of the sensor pairs observed in this portion of the study was well within the total range in sensor responses observed from the cold room tests (paragraph 32). Of special interest is that the EWIT sensor containing excess moisture (E3) did not suffer any appreciable loss in signal level with respect to E1. This again indicates that moisture within the sensor has little effect on EWIT response due to below-freezing temperatures.

50. The above results indicate that as the medium becomes more rigid with increased frost penetration, the displacement of the soil decreases and causes a decreased output from the sensor.

Variation in response
along one sensor

51. The longitudinal variation in response of the four EWIT sensors was investigated using the data obtained from the tests performed with the calibrated creeper. These data were collected at test points A, B, and C (Figure 12), and the results are shown in Figures 13-16 for E1, E2, E3, and E4, respectively. These data show that the sensor buried at 23 cm suffered the most change in response with respect to the location of the source along the sensor. This variation in longitudinal response decreased, however, with an increase in frost penetration.

52. As shown in the above comparisons, the data obtained from the calibrated creeper tests exhibited much lower signal levels than those obtained from the man-walking tests. The scatter in these data is

partially attributable to low output levels that, in most cases, made it difficult to identify appropriate signal levels within the background noise.

53. Although the calibrated creeper was designed to produce low-frequency (0.5-Hz) surface loads that are somewhat lower (conservative) than average forces produced by a man creeping (walking stealthily),* the extraordinarily low level signals obtained in these tests are assumed to be more appreciably affected by the frozen-ground condition. As discussed in previous studies,** frozen-ground conditions have been observed to attenuate the low-frequency response of the EWIT sensor.

Summary of Analysis of Frozen-Soil Tests

54. The results of the frozen-ground tests indicate the following:

- a. An increase in the depth of frozen ground can cause a comparable decrease in EWIT sensor response by as much as 30 db.
- b. The change in response of the EWIT with increased frost penetration may be lower with increased burial depth. However, the increased burial depth may cause the output to be indistinguishable from background and system noise.
- c. During the conduct of these tests, output variation as a function of longitudinal distance along individual sensors and as a function of different sensors at the same burial depth was relatively small.
- d. Signal levels obtained from response tests using the calibrated creeper were extraordinarily low. This situation is comparable to previous studies** that indicated low EWIT response levels at low frequencies under frozen-ground conditions.

* Miller, op. cit., p. 5.

** Erianne, op. cit., p. 3.

PART IV: UNFROZEN SOIL TESTS

55. Two EWIT sensors were deployed at a depth of 23 cm at a line sensor test site at WES to examine the change in response of the EWIT sensor with changes in the shear modulus of the emplacement media. Each sensor was deployed with one half of its 15-m length in natural soil (loess) and the other half in a soil-cement mixture and/or concrete.

Site Description

56. The EWIT response tests were conducted at a site at WES (lat. 32°18'23"N, long. 90°51'14"W) at which numerous line sensor tests have been conducted. The natural soil at this site consists of a wind-deposited clayey silt (loess), commonly found in this area. Seismic wave velocity tests showed that the material had a compression wave velocity of 350 m/sec and a shear wave velocity of approximately 120 m/sec. The vegetation at the site consists of short grasses and a wooded area having trees with an average height of approximately 15 m.

57. The soil-cement site, a relatively small (6 by 5.5 m) section of the WES MAID-MILES test area,* was chosen for EWIT response testing because its shear modulus was comparable to that of a frozen soil. The natural soil was removed to a depth of 1 m, mixed with 33 percent sand and 6 percent portland cement, and mechanically recompact to a density of 1.92 g/cm³. Measured seismic characteristics data indicated that this area had a compression wave velocity of 1100 m/sec and a shear wave velocity of 600 m/sec.

58. The concrete site is another small (6 by 5 m) section in which a 45-cm-thick bed of concrete was poured at design specifications for airfield runways. In this case the EWIT sensor was installed at a depth of 7.5 cm and the trench was backfilled with epoxy.

* Cress, op. cit., p. 16.

Conduct of Comparative Tests

59. Man-walking tests were conducted directly over each cable in the loess, soil-cement, and concrete. During the conduct of the tests for the concrete section, it was observed that no man-walking signature could be detected above system noise. Consequently, the remainder of the tests were conducted over the EWIT sensor colocated in loess and soil-cement.

Results and Analysis of Data

60. The peak-to-peak amplitude signals of EWIT sensor were compared for the man creeping directly over the transducer in the loess and the soil-cement material. The average signal levels were 685 and 56 microvolts, respectively. This indicates a 21.75-db decrease in signal level of the more rigid soil-cement material as compared to the loess material. This loss in signal level is approximately the same as that found in the comparisons of the frozen and unfrozen conditions in paragraph 45.

PART V: CONCLUSIONS AND RECOMMENDATIONS

Conclusions

61. From the analysis of the results of the tests conducted in this study, the following conclusions have been made:

- a. Below-freezing temperatures do not cause an appreciable loss in EWIT response (paragraph 33). Signal losses were not observed even after introducing moisture to the interior of the sensor (paragraph 49).
- b. Changes in sensor orientation can cause large changes in relative sensor output. This may be caused by the relocation of the points of contact of the teflon-coated wire (paragraph 28).
- c. Frozen soil can cause a significant loss in EWIT signal amplitude. The loss in output level is generally proportional to the depth of penetration of the frost until penetration approaches the depth of burial of the sensor and then output approaches a constant signal level with increased frost penetration (paragraph 48).
- d. A relatively low EWIT response was observed from low-frequency (0.5-Hz) source signals during frozen ground conditions (paragraph 53).
- e. The rigidity (shear modulus) of the emplacement media directly affects the relatively low-frequency (less than 10-Hz) signal output of the EWIT sensor. Comparative tests show the same decrease in EWIT output for loess versus soil-cement as for unfrozen versus frozen soil (paragraph 60).
- f. The connections presently being used for EWIT sensor are easily broken, which could cause encroachment of moisture and other contaminants to the interior of the sensor (paragraph 33).

Recommendations

62. From the results obtained in this study, it is recommended that

- a. Tests be performed under controlled frozen-ground conditions in which sensor response comparisons of the EWIT sensor and other types of sensors, such as the Magnetic Intrusion Line Sensor (MILES) and the Buried Line

Intrusion Detector (BLID) are made. This information should provide a direct comparison of individual sensor types under identical terrain conditons.

- b. Controlled frozen-ground tests be performed on the EWIT in which the intrusion, strumming, and accelerometer modes of response are investigated. These data will give a complete description of EWIT response as a function of frost depth.
- c. Detailed tests be performed in frozen-ground conditions at low frequencies (less than 2 Hz) in which the forces provide a complete description of EWIT response at these low frequencies.
- d. A more durable connection be developed for the EWIT sensor.

Table 1
Beam-Spring-Mass Design

<u>Criteria for System Specifications</u>					
Frequency, Hz	1	3	5	7	10
Particle velocity, cm/sec $\times 10^{-3}$	10	33	50	75	150
Beam deflection at midspan, cm $\times 10^{-3}$	1.6	2.2	1.5	1.5	3.0

Beam Specifications

Type - 10 \times 15 cm Wide-Flange Aluminum

Length = 2 m

Young's modulus = 0.7×10^{11} pa

Moment of inertia = 905 cm⁴

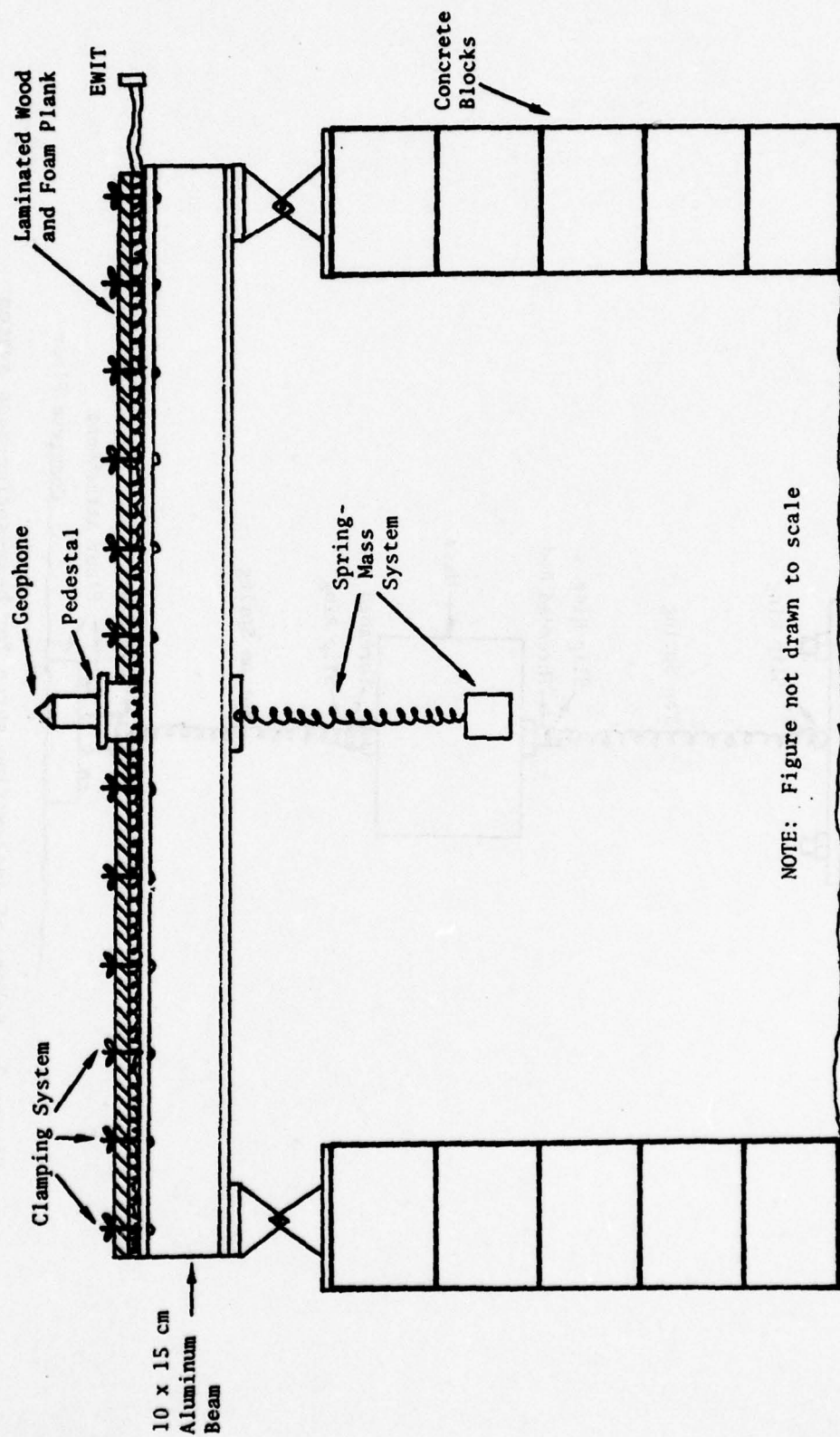
Spring-Mass Specifications

Frequency, Hz	1	3	5	7	10
Size of mass, kg	9	9	2.3	2.3	2.3
Spring constant, kg/cm	1.77	16.0	11.1	21.7	44.4
Initial spring deflection, cm	17	2.5	2.5	1.25	1.25

Table 2
Results of Beam Comparison Tests

Frequency Hz	Initial Spring Deflection cm	Midspan Particle Velocity cm/sec $\times 10^{-3}$	
		<u>Measured*</u>	<u>Specified</u>
1	17.0	10.6	10.0
3	2.5	30.6	33.0
5	2.5	46.8	50.0
7	1.25	81.3	75.0
10	1.25	138.0	150.0

*Values averaged for 10 tests at each frequency.



NOTE: Figure not drawn to scale

Figure 1. Schema of beam-spring-mass system

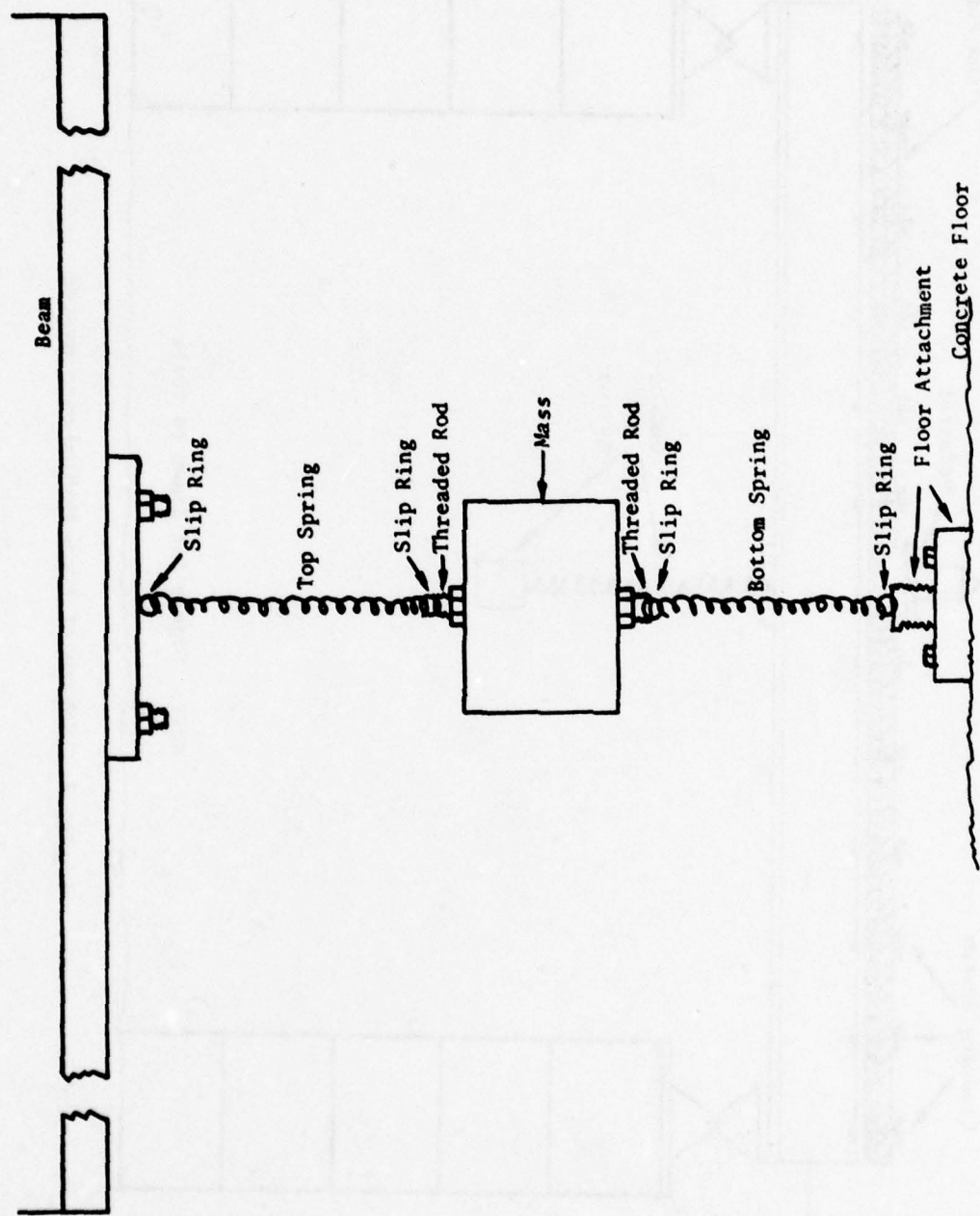


Figure 2. Schema of dual-spring setup for beam-spring-mass system

NOTE: Enclosed sample points are for a single clamping arrangement

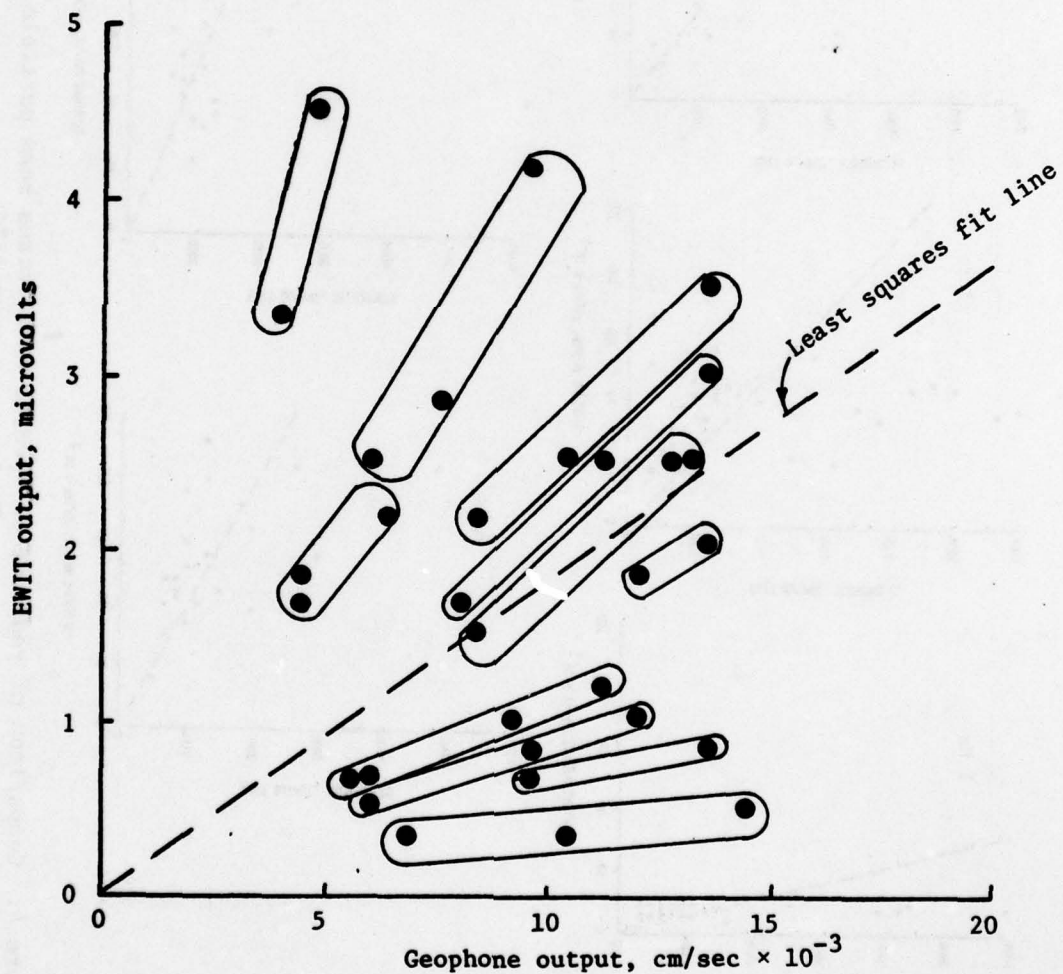


Figure 3. Comparison of EWIT response and beam particle velocity at midspan for fixed clamping arrangements

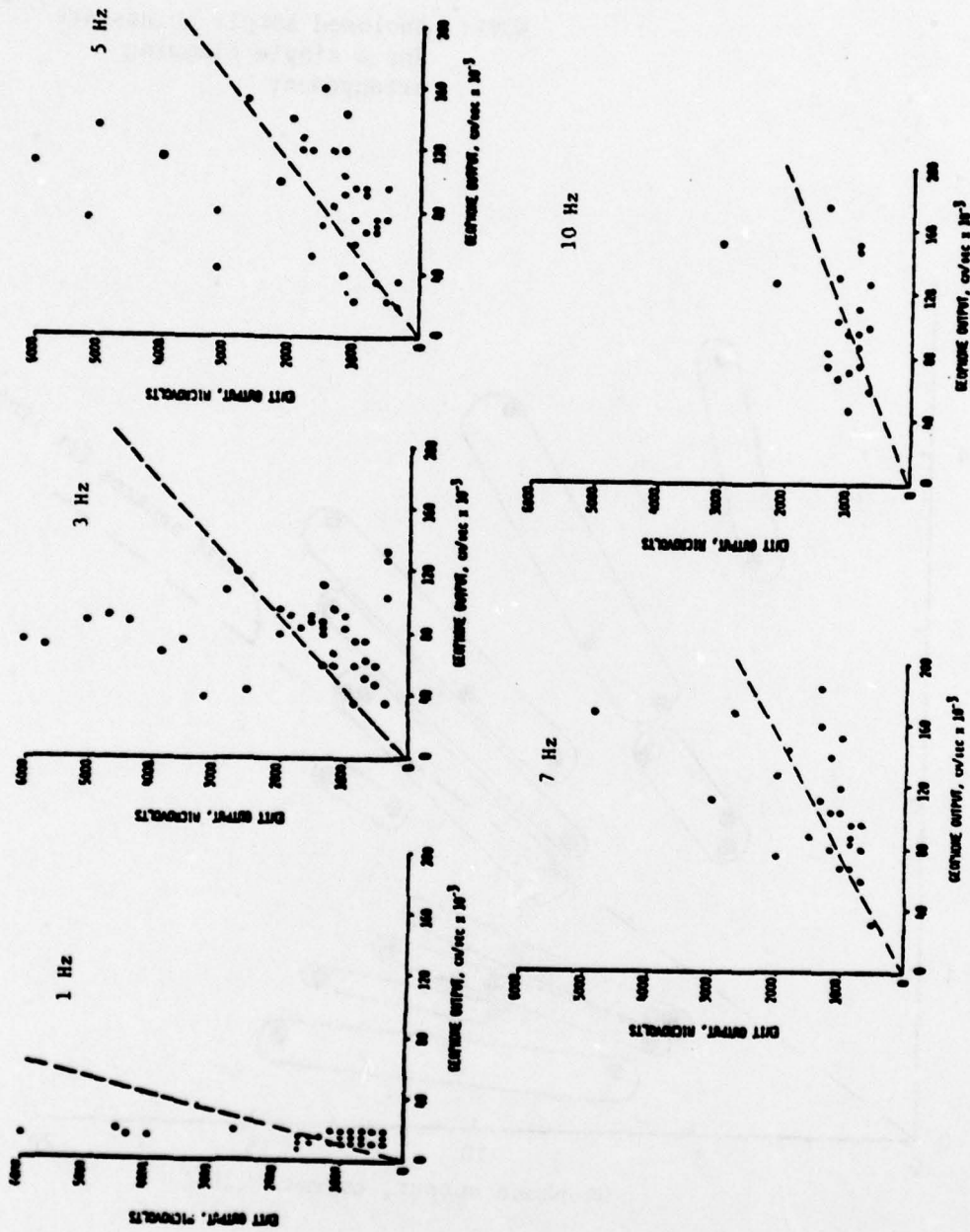


Figure 4. Comparison of response of special EWIT versus beam particle velocity at midspan.
Test temperature 15°C



Figure 5. Comparison of response of special EWIT versus beam particle velocity at midspan.
Test temperature -10°C



Figure 6. Comparison of response of standard EWIT versus beam particle velocity at midspan.
Test temperature 15°C

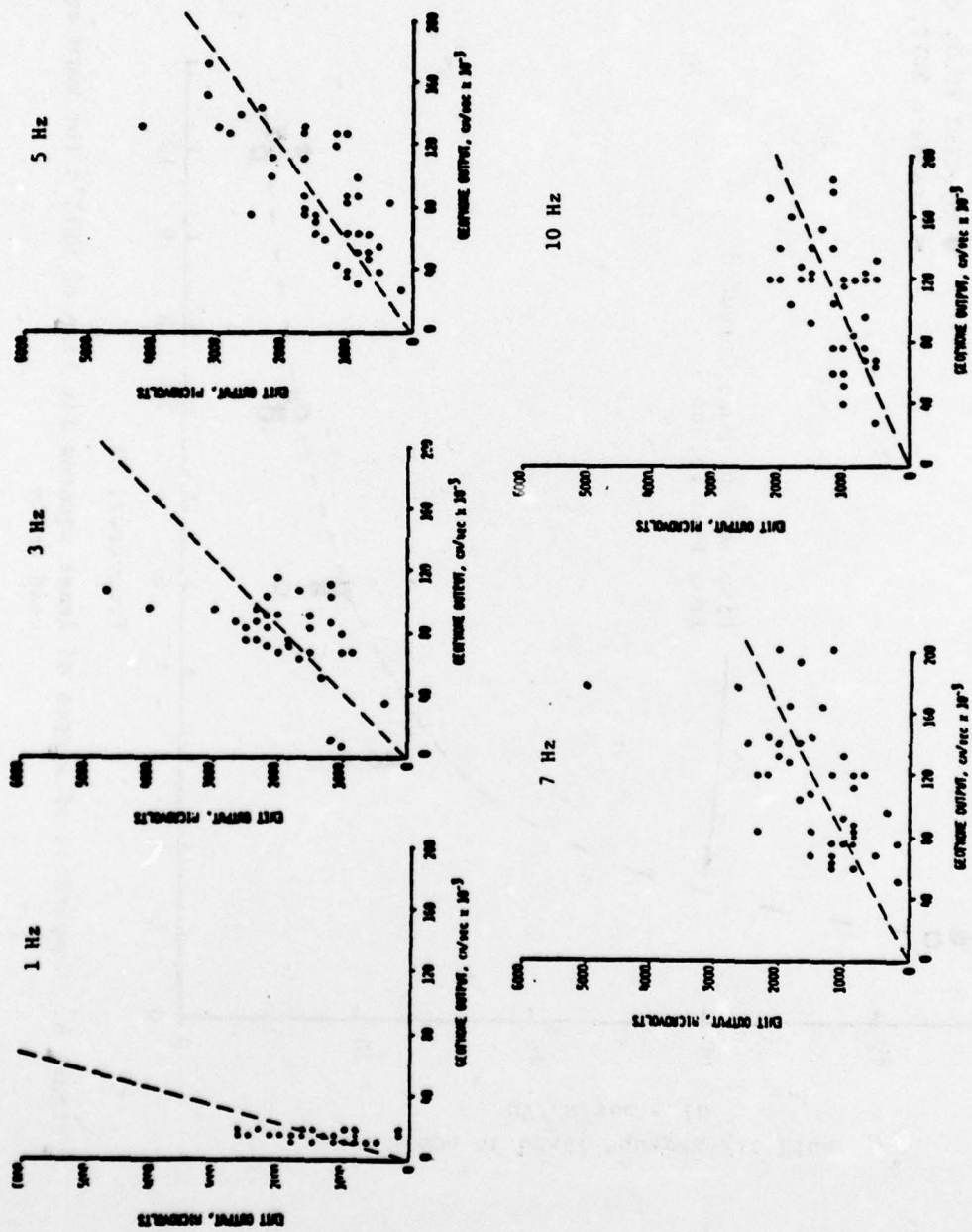


Figure 7. Comparison of response of standard EWIT versus beam particle velocity at midspan.
Test temperature -10°C

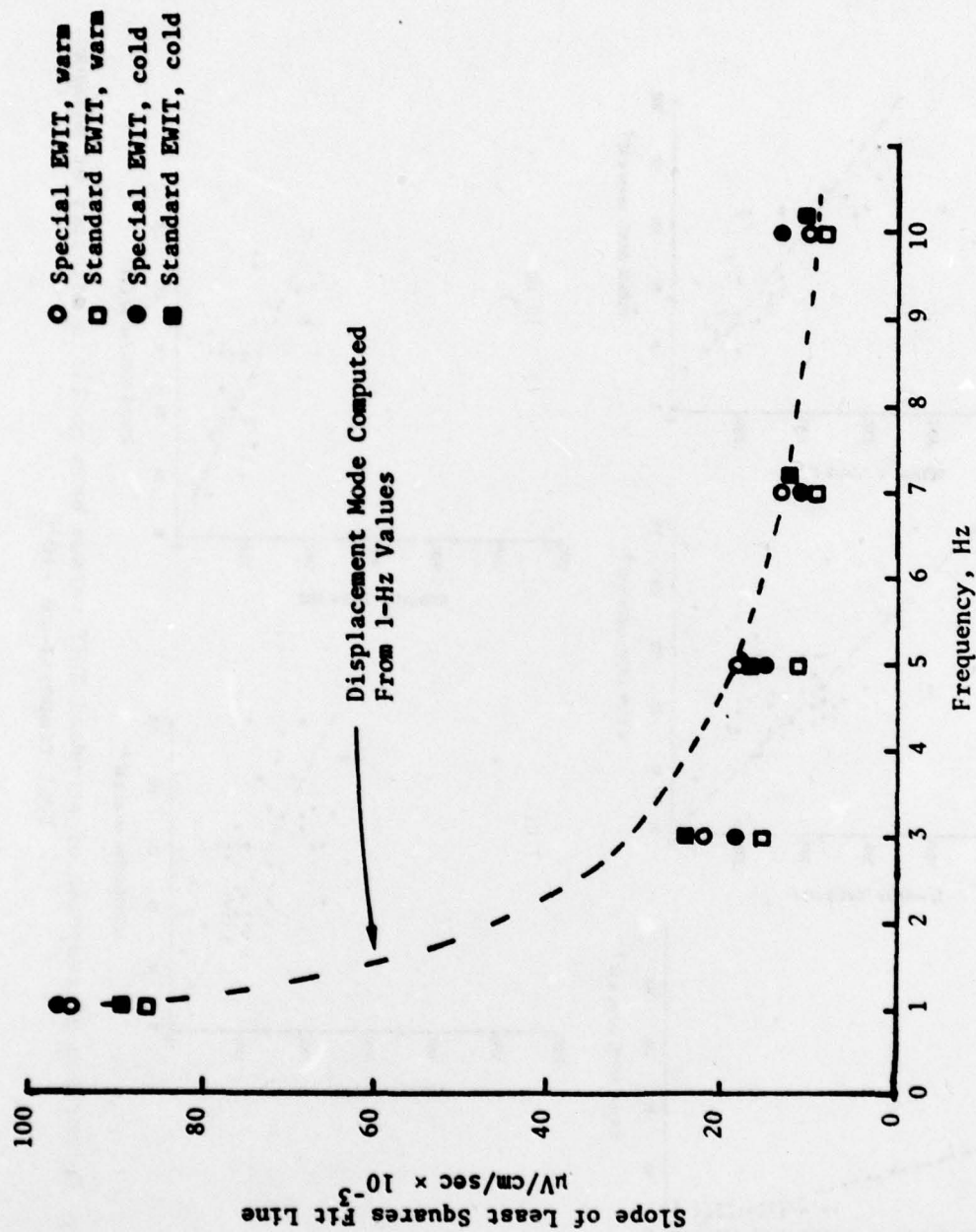


Figure 8. Comparison of slopes of least squares fit line of EWIT's for warm and cold tests

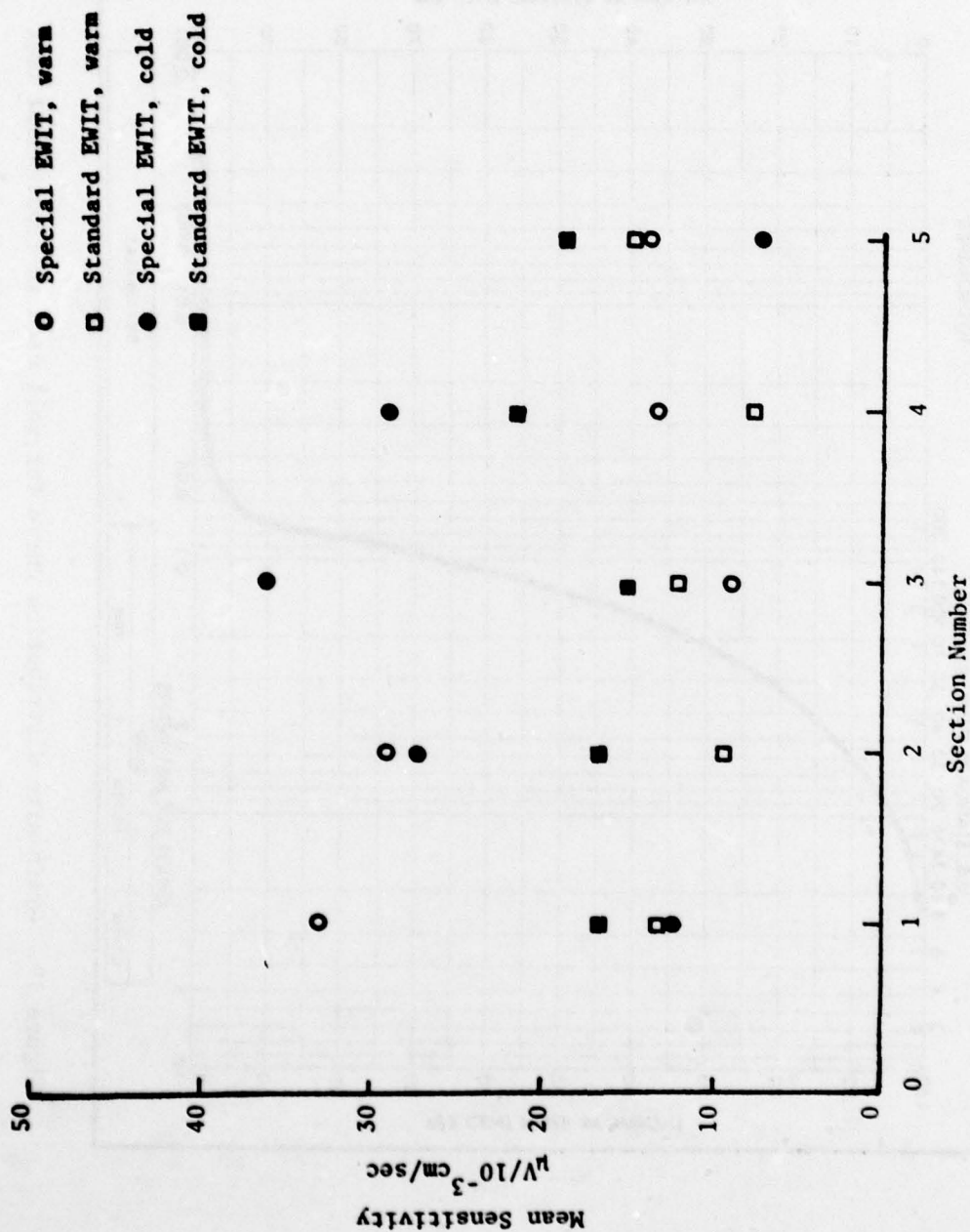


Figure 9. Comparison of the mean sensitivity of EWIT and geophone output for five sections of the EWIT sensor

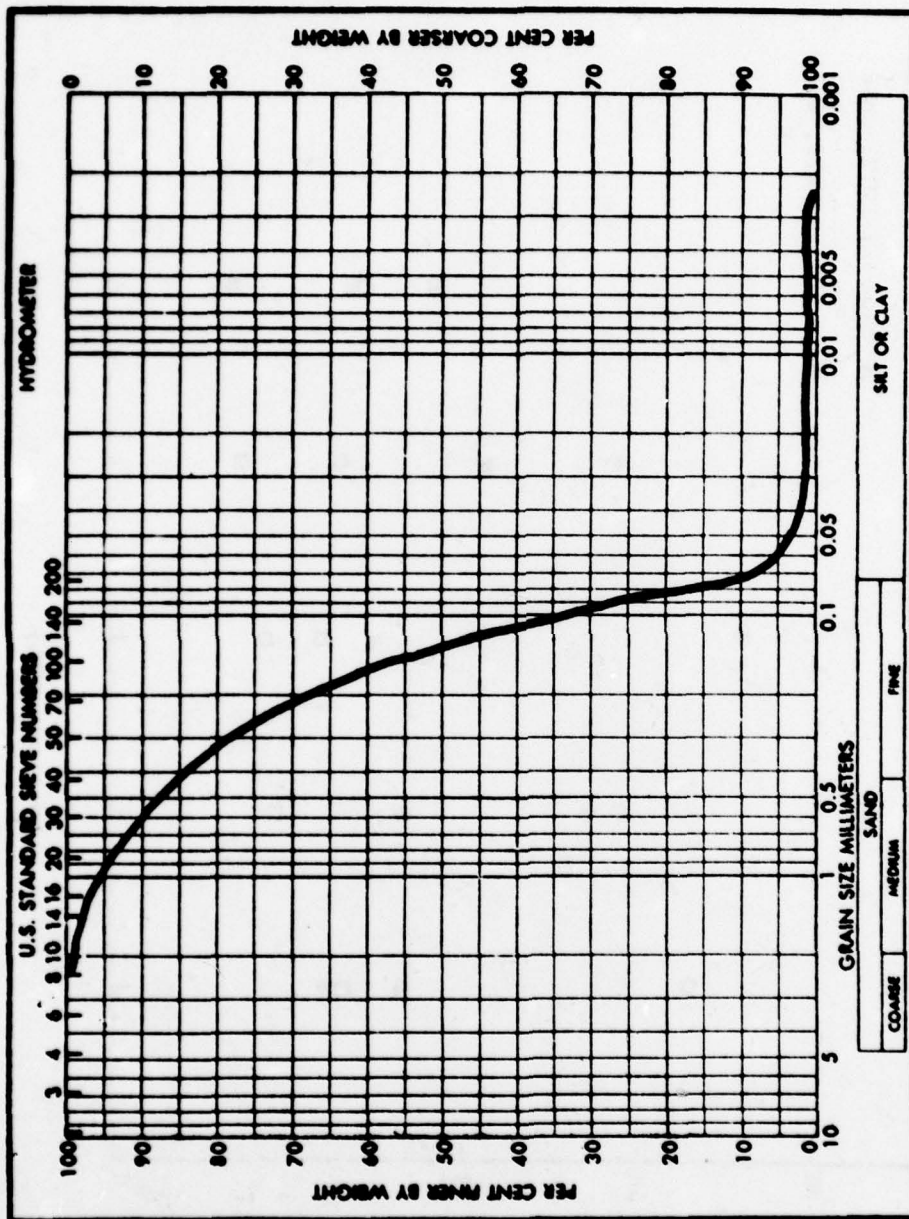
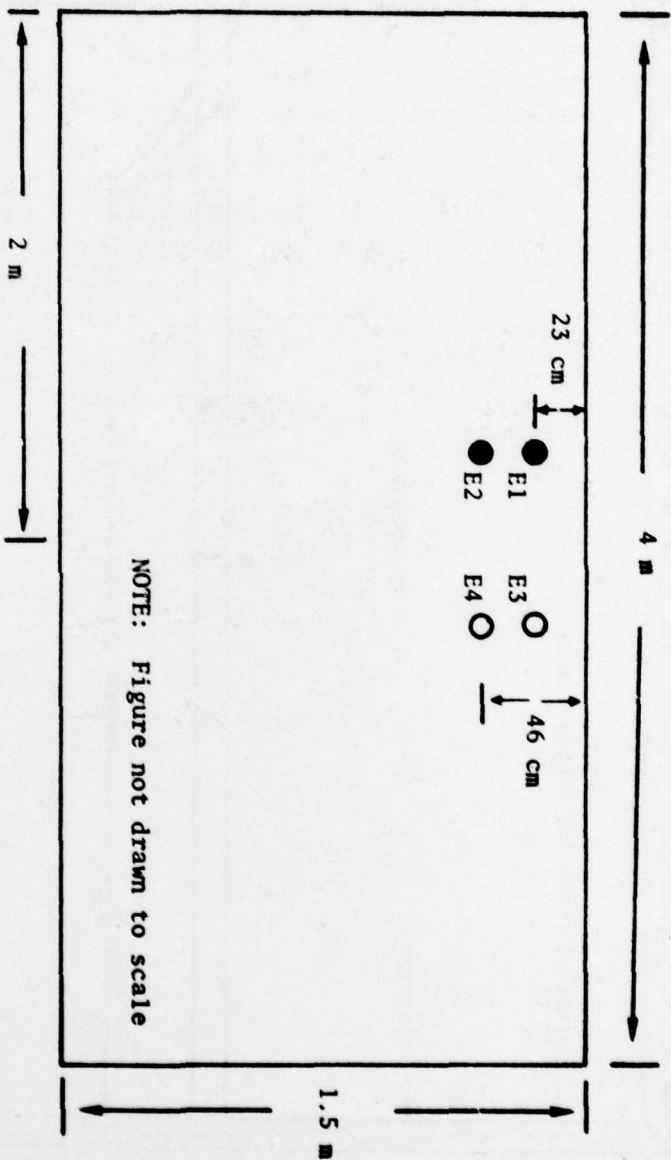


Figure 10. Grain-size distribution curve for soil used in frozen-soil test



- Standard sensors
- Special sensors

Figure 11. Configuration of EMIT sensors for frozen-soil tests
(profile A-A Figure 12)

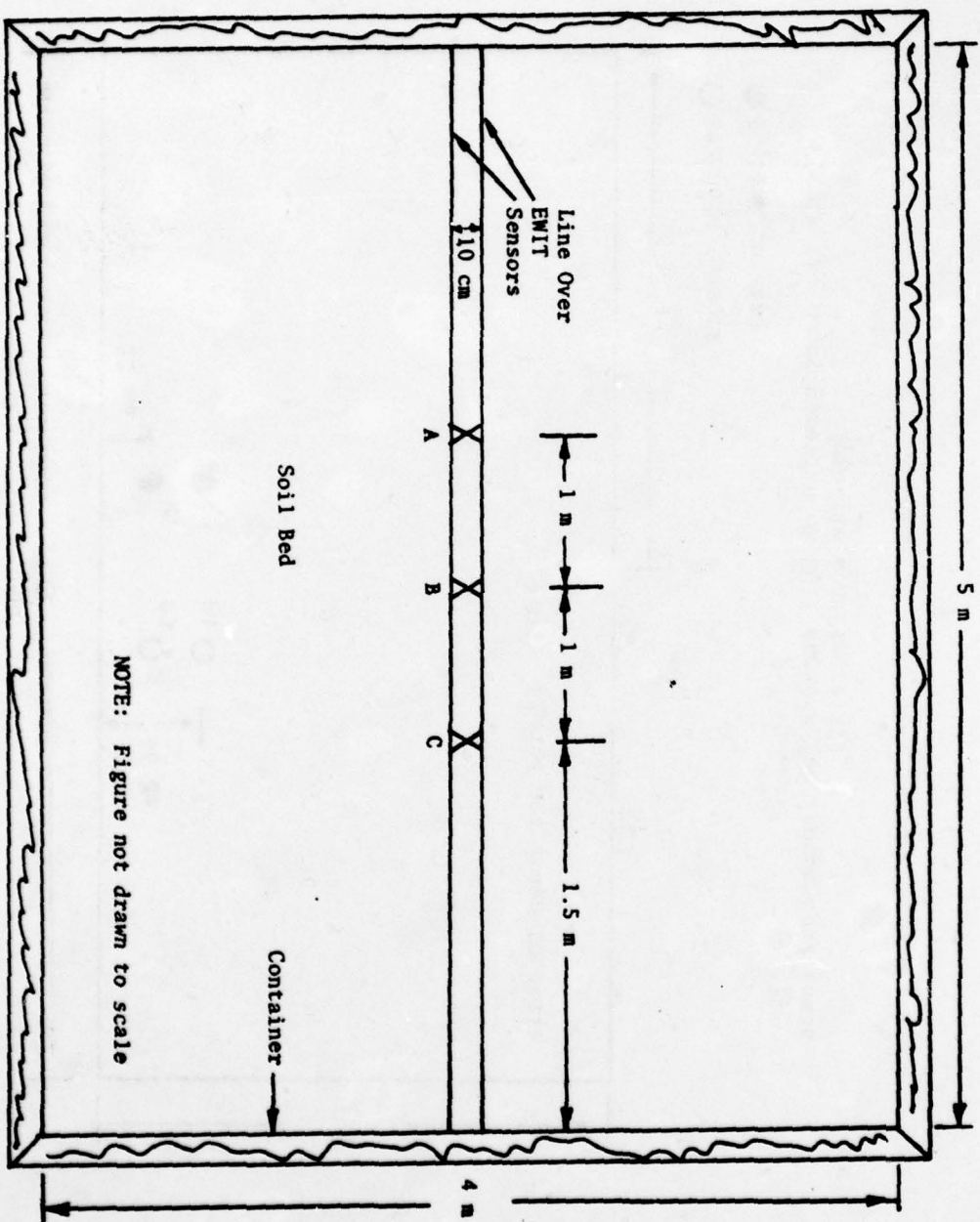


Figure 12. Location of test points for frozen-soil calibrated creeper tests

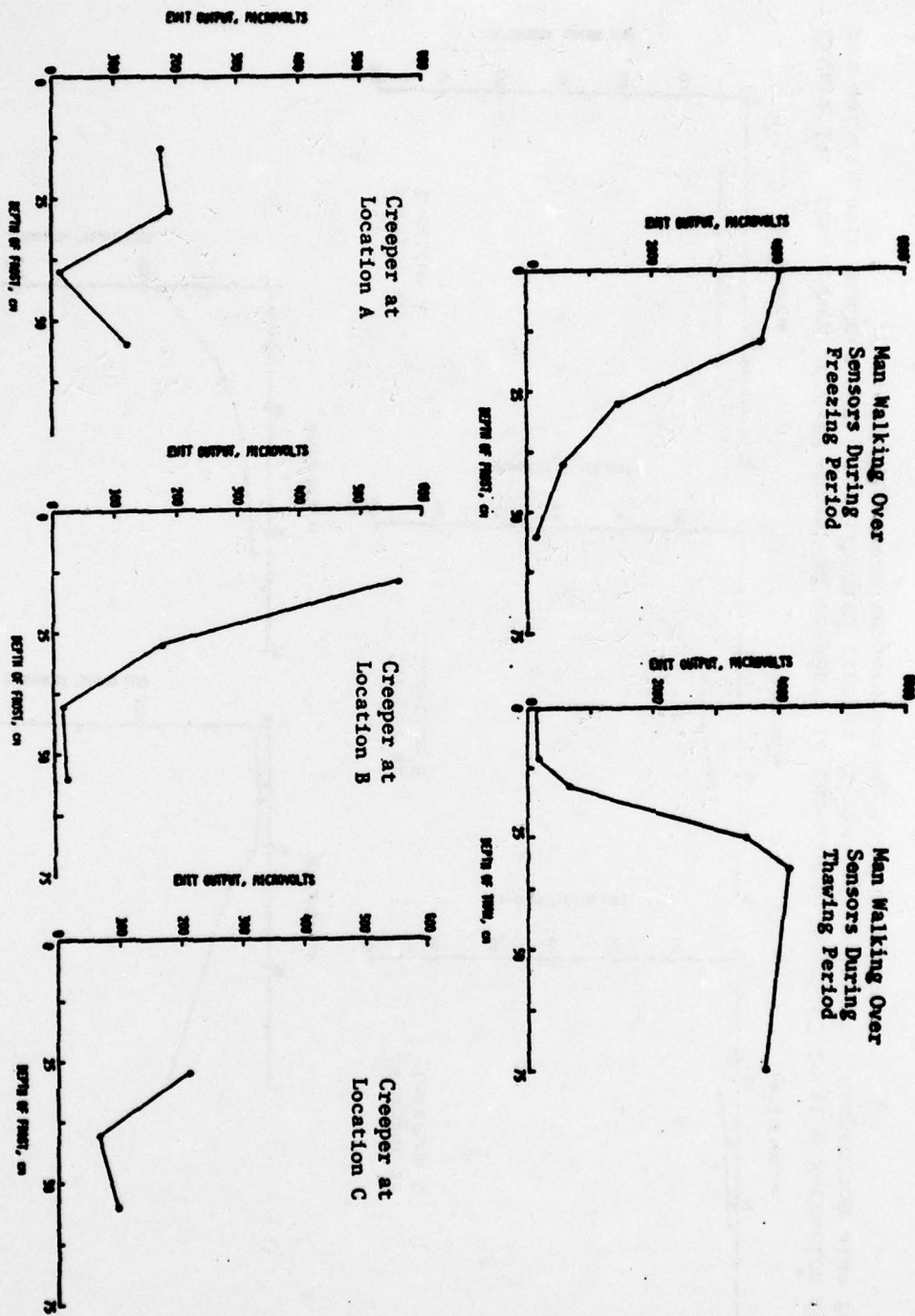


Figure 13. Comparison of EMIT sensor EI response to changes in depth of frost penetration for man walking over sensors and for calibrated creeper at various locations. Comparison also for man walking over sensors during thawing period

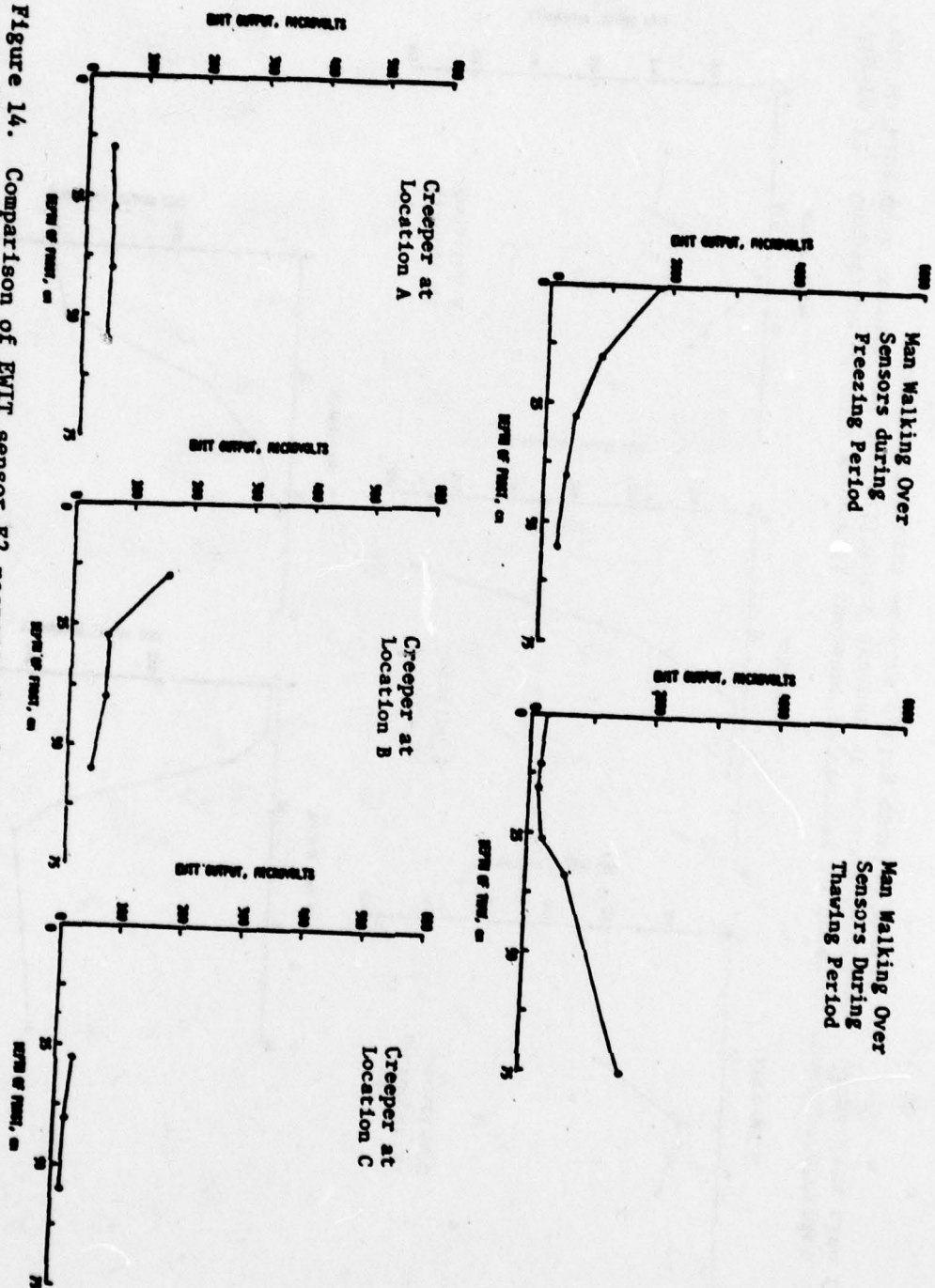


Figure 14. Comparison of EWIT sensor E2 response to changes in depth of frost penetration for man walking over sensors and for calibrated creeper at various locations. Comparison also for man walking over sensors during thawing period

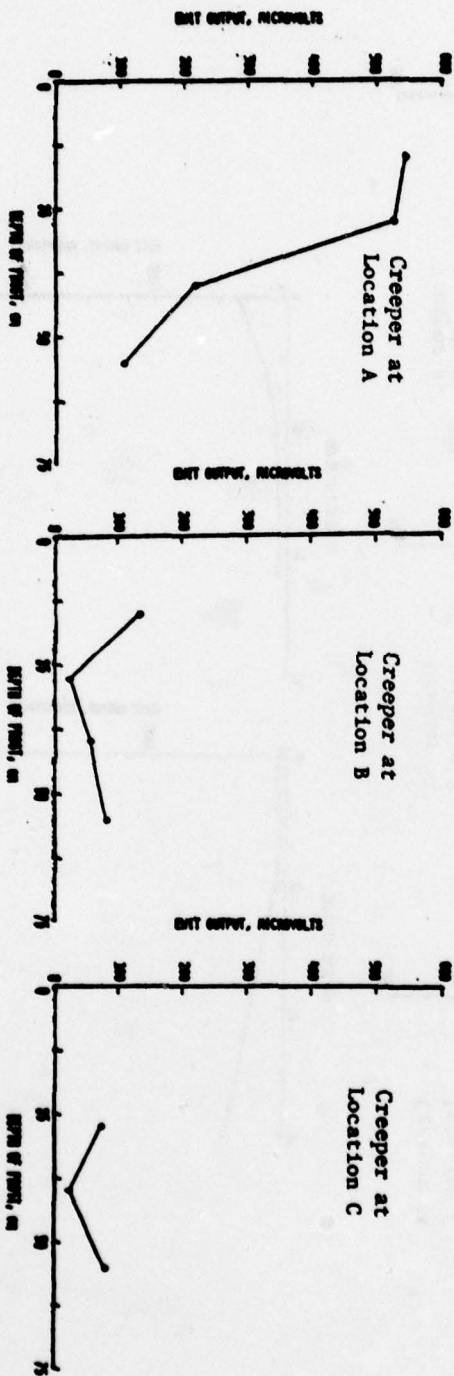
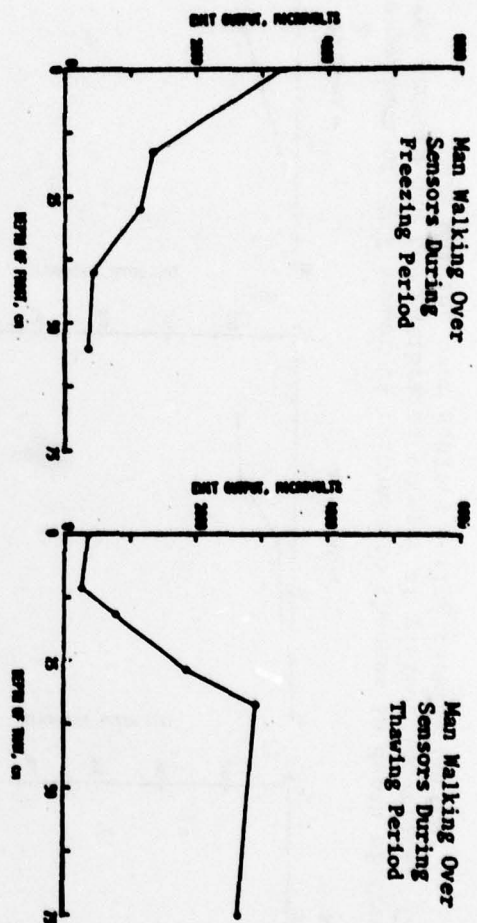


Figure 15. Comparison of EWIT sensor E3 response to changes in depth of frost penetration for man walking over sensors and for calibrated creeper at various locations. Comparison also for man walking over sensors during thawing period

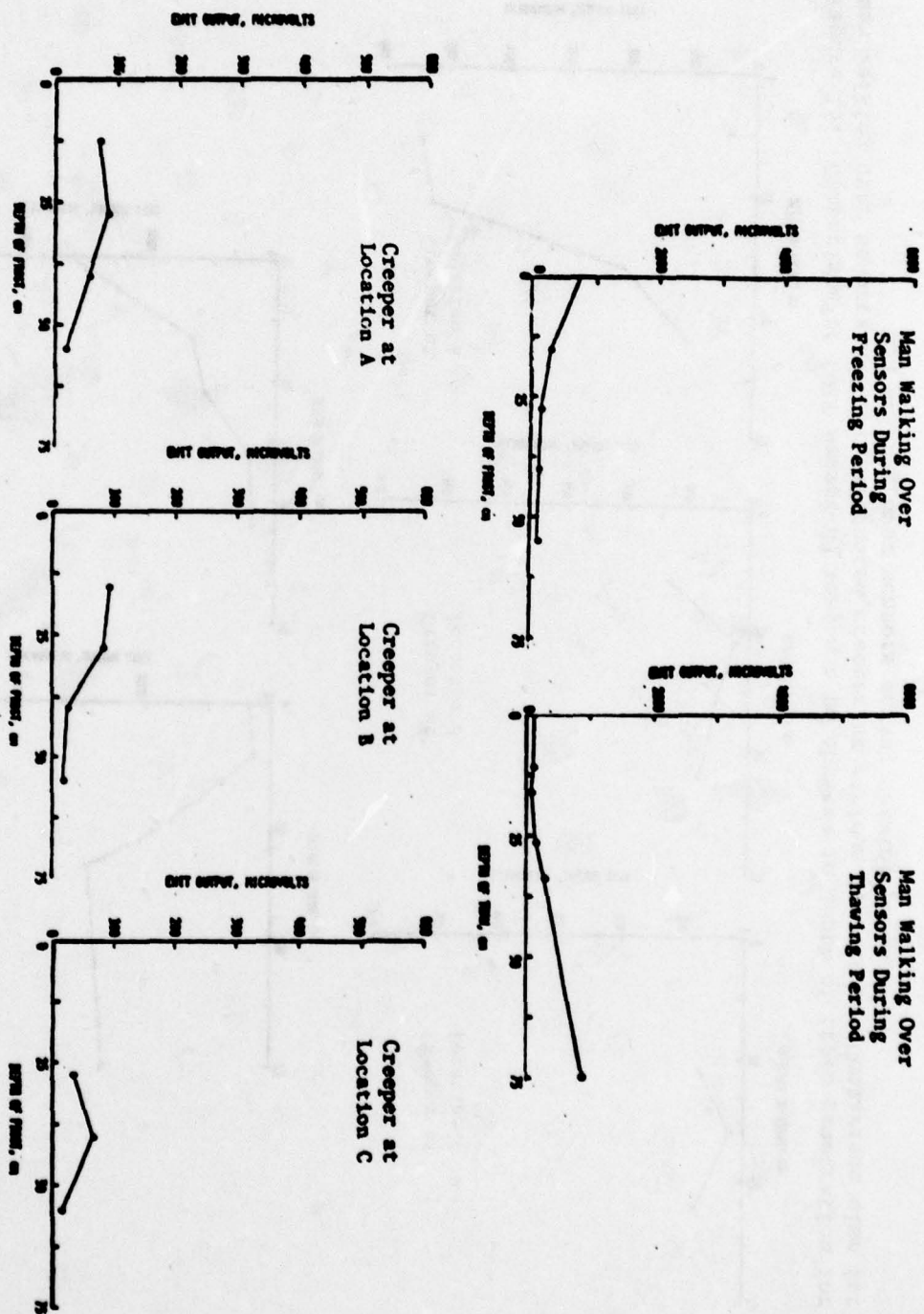


Figure 16. Comparison of EMIT sensor E4 response to changes in depth of frost penetration for man walking over sensors and for calibrated creeper at various locations. Comparison also for man walking over sensors during thawing period

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Miller, Charles A

Effects of freezing temperatures and frozen-ground conditions on enclosed-wire-in-tube response / by Charles A. Miller. Vicksburg, Miss. : U. S. Waterways Experiment Station ; Springfield, Va. : available from National Technical Information Service, 1979.

22, [18] p. : ill. ; 27 cm. (Miscellaneous paper - U. S. Army Engineer Waterways Experiment Station ; EL-79-2)

Prepared for Rome Air Development Center, Griffiss Air Force Base, N. Y.

Includes bibliographical footnotes.

1. Enclosed-wire-in-tube. 2. Frozen soils. 3. Sensors. 4. Temperature effects. 5. Transducers. I. United States. Air Development Center, Rome, N. Y. II. Series: United States. Waterways Experiment Station, Vicksburg, Miss. Miscellaneous paper ; EL-79-2.
TA7.W34m no.EL-79-2